Quality of Ambulant Measures of Distance, Speed, Load and Energy Consumption During Military Operations

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ABSTRACT

During training and operations, soldiers are exposed to a number of factors that influence their physical and cognitive performance. These factors are induced by the environment (e.g. heat, altitude, dust, wind, rain), physical job requirements (e.g. carrying loads, walking, sleep deprivation) and mental stress (e.g. decision making, exams, combat stress). The majority of these factors have a negative impact on the operational readiness of soldiers. In 2008 a 4-year research program called 'Military Performance and Health Monitoring' was started. One of the goals of this program is to test or develop devices for ambulatory monitoring of environmental, physical and mental factors. In this paper, we describe three separate studies that focus on the quality of measuring devices.

Studies

1. *Validity of the Sensewear Pro$_3$ Armband in estimating energy expenditure and sleep duration. The validity of the Sensewear Pro$_3$ armband towards energy expenditure was measured on a treadmill. Ten healthy subjects performed a series of tests. Variations were made in walking speed (4, 7 and 10 km/h), load (0 and 23 kg), arm position (with and without arm swing), slope (0% and 10%) and clothing (with or without additional clothes). Energy consumption was measured by indirect calorimetry (Metamax 3b, Cortex). The ability of the Sensewear to measure sleep duration was measured over 5 days in 4 subjects. Sleep duration was also monitored by use of a log.*

2. *Qualifying load, speed and slope by use of accelerometry. In this study the influences of variations in speed (3, 5 and 7 km/h), load (11, 24 and 36 kg) and slope (0% and 5%) on the output of a tri-axial accelerometer (Spi-Elite, GPSports) was measured. Eight subjects participated in this study.*

3. *Quality of GPS signals in measuring distances. GPS data is known to be less accurate in urban areas or in forests. In this study, different GPS systems were compared in open terrain, forests and during a zigzag track.*

1.0 STUDY 1: VALIDITY OF THE SENSEWEAR PRO$_3$ ARMBAND IN ESTIMATING ENERGY EXPENDITURE AND SLEEP DURATION

1.1 Introduction

The Sensewear Pro$_3$ Armband is a new energy expenditure testing device, available since 2007. This ambulant instrument gathers raw physiological data, including movement, heat flux, skin temperature, near body temperature and galvanic skin response. The battery lasts approximately 14 days when worn

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14. ABSTRACT
During training and operations, soldiers are exposed to a number of factors that influence their physical and cognitive performance. These factors are induced by the environment (e.g. heat, altitude, dust, wind, rain), physical job requirements (e.g. carrying loads, walking, sleep deprivation) and mental stress (e.g. decision making, exams, combat stress). The majority of these factors have a negative impact on the operational readiness of soldiers. In 2008 a 4-year research program called Military Performance and Health Monitoring was started. One of the goals of this program is to test or develop devices for ambulatory monitoring of environmental, physical and mental factors. In this paper, we describe three separate studies that focus on the quality of measuring devices.

15. SUBJECT TERMS

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continuously. It stores approximately 10 days of continuous physiological and lifestyle data with default configuration. Sensewear software calculates energy expenditure without measuring heart rate.

In this study the reliability and the validity of the Sensewear Pro_3 armband towards energy expenditure was measured. Also was looked at the ability of the Sensewear to measure sleep duration

1.2 Methods

1.2.1 Design

Validity: 10 subjects (average age 40 yrs ± sd 11.9) performed a series of tests on a treadmill (Woodway - ELG70). Variations were made in walking speed (0, 4, 7 and 10 km/hr). Energy consumption was measured during 15 minutes by Sensewear Pro_3 armband (BodyMedia, Pittsburgh) worn on the right upper arm (on triceps). Indirect calorimetry (Metamax 3b, Cortex) served as the criterion measure in this study.

MetaMax results are calculated to energy expenditure (kcal.min^{-1}) by multiplying oxygen uptake (L.min^{-1}) by caloric equivalent based on the RER. The Sensewear results (kcal) are calculated to kcal.min^{-1}.

Reliability: Test-retest reliability is calculated using the results of 8 subjects who walked with 4 km/hr during 15 minutes with no load.

Sleep duration: The ability of the Sensewear to measure sleep duration was measured over 5 days in 4 subjects. They put on the Sensewear armband 1 hour prior to sleep, during sleep and for 10 minutes after awakening. Sleep duration was also monitored by means of a log (own perception).

1.2.2 Statistical Analysis

Statistical analysis was performed using SPSS (version 15.0). Data were analyzed for each test protocol using Student t-test (statistical significance was defined $p \leq 0.05$) to compare both techniques, and Pearson correlation coefficient (correlation was defined high $r \geq 0.90$, good $0.80 \leq r < 0.90$, sufficient $0.70 \leq r < 0.80$ and poor $r < 0.70$) to test predictability. Reliability was analyzed using coefficient of variation.

Coefficient of variation (cv) is calculated by:

$$cv = \frac{SD/\sqrt{2}}{(X_1 + X_2)/2} * 100$$

Poor reproducibility:	cv ≥ 10%
Sufficient reproducibility:	5% ≤ cv < 10%
Good reproducibility:	cv < 5%

1.3 Results

1.3.1 Validity

Table 1 and figure 1 show the mean energy expenditure (kcal/min) measured by Sensewear and by Metamax at walking speed of 4, 7 and 10 km/hr during 15 minutes and during being seated for 15 minutes. Sensewear data were used to predict Metamax values by calculating regression equations.

Table 1 shows also these regression equations.

Table 1: Energy expenditure measured by Sensewear and by Metamax during sitting and at walking speed of 4, 7 and 10 km/hr.

	Sensewear (SW)		Metamax (MM)		Regression equation	SEE	R^2-adjusted
	Mean kcal/min	sd	Mean kcal/min	sd			
Seated	1.18	0.12	1.78	2.60	MM = 1.28*SW + 0.27	0.23	0.25
4 km/hr	4.95	0.86	4.10	0.55	MM = 0.53*SW + 1.45	0.35	0.61
7 km/hr	8.68	1.96	8.93	1.96	MM = 0.74*SW + 2.48	0.91	0.71
10 km/hr	11.58	1.98	13.80	2.48	MM = 1.08*SW + 1.26	1.31	0.72

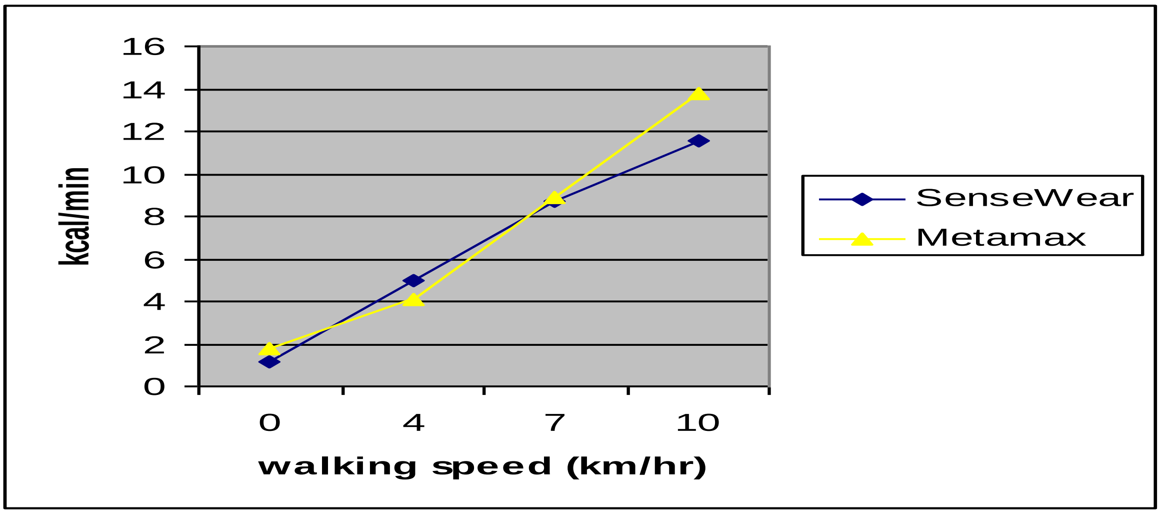

Figure 1: Energy expenditure measured by Sensewear and by Metamax during sitting and at walking speed of 4, 7 and 10 km/hr.

<u>0 km/hr (sitting)</u>
Sensewear measurements show lower values compared to Metamax. The Sensewear underestimated 33% on average. There is a significant difference between Sensewear and Metamax (p=0.000). A correlation was found of 0.574.

<u>Walking 4 km/hr</u>
When walking at 4 km/hr Sensewear shows higher energy expenditure than Metamax. The Sensewear has a larger spread, compared to sitting. The Sensewear overestimated 20 % on average. The correlation is higher, r=0.822, and between the two sets the difference is significant (p=0.001).

<u>Walking 7 km/hr</u>
At 7 km/hr there is no significant difference between both measurements (r=0.862, p=0.438).

<u>Walking 10 km/hr</u>
At 10 km/hr Sensewear shows lower energy expenditure than Metamax: an underestimation of 16 %. A correlation was found of 0.868 and there is a significant difference between both measurements, p=0.000.

1.3.2 Test-Retest Reliability

Eight subjects performed the 4 km/h walking test twice. Table 2 shows the test-retest reliability results for Sensewear and Metamax.

Table 2: Test (mean 1, sd1) and retest (mean 2, sd 2) energy expenditure results (kcal/min) for Sensewear and MetaMax at walking at 4 km/hr.

	mean 1 (kcal/min)	sd 1	mean 2 (kcal/min)	sd 2	SE mean	cv
SenseWear	5.08	0.832	5.10	0.733	0.88	12.2%
MetaMax	4.21	0.440	4.31	0.454	0.29	4.2%

Both the SenseWear and Metamax data show no significant differences between the first and the second test. Sensewear (poor reproducibility) shows a larger coefficient of variation (cv) than Metamax (good reproducibility).

1.3.3 Sleep Detection

The ability of the Sensewear to measure sleep duration was measured over 5 days in 4 subjects. Sleep duration was also monitored by means of a log (own perception). Table 3 presents the results of sleep detection.

Table 3: Results of sleep detection by Sensewear and by own perception (log).

	Own perception		**Sensewear**		**Difference**			
	Mean (min)	**sd**	**Mean (min)**	**sd**	**Mean (min)**	**sd**	**Corr.**	**Sig.**
In bed (lying)	470	65	476	70	-6	15	0.98	0.12
In bed (sleeping)	418	75	402	68	17	42	0.83	0.10

High correlations were found between own perception and Sensewear for lying in bed (r=0.98) and sleeping in bed (r=0.83). Neither lying nor sleeping show a significant difference between Sensewear measurements and own perception.

1.4 Discussion

1.4.1 Validity

The overall results of measuring energy expenditure by Sensewear in relation to the criterion measure (oxygen uptake) show conflicting results. Measurements reveal an underestimation at rest and at 10 km/hr, an overestimation at 4 km/hr and a fairly good estimation at 7 km/hr. Because of these conflicting results the use of one single regression equation for different walking speeds is not an option.

At rest (0 km/hr) Sensewear measurements show a energy expenditure with a 33 % underestimation compared to Metamax. Other studies are not clear about the performance of the Sensewear during rest. Baldini et al (13) indicate a 4 % underestimation during rest, while Deemer (14) measures an overestimation of 25 %. However, during rest energy expenditure is so low that the error in measuring total energy expenditure will be negligible.

This is also the case because the underestimation is compensated by the overestimation at 4 km/hr, or low activity level. Sensewear measures are too high on low activity level and are not valid for this activity. The results of this study are convergent with other studies. Fruin & Rankin (16) found percentages overestimation of 13 – 27 %. Calabro (2) showed a large overestimation on different low walking velocities.

At 7 km/hr, the marching speed of military, Sensewear data seems valid: results of Sensewear and Metamax agree. Few studies are done at this speed. Somewhat comparable is the Baldini study at 8 km/hr: a 2 % overestimation.

At 10 km/hr Sensewear underestimates energy expenditure. Similar studies were not found.

The fact that measurements were taken only over a period of 15 minutes may cause the conflicting results. Recent research (measurements over days) indicates better results in estimating energy expenditure.

1.4.2 Test-Retest Reliability

Test-retest measurements show poor reproducibility for Sensewear for measurements of short duration (15 minutes). No literature was found on test-retest reliability of Sensewear. Metamax measurements correspond with earlier research looking at test-retest reliability (12). Mean coefficient of variation values of 5.5% were found on four different working loads.

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2.0 STUDY 2: QUALIFYING LOAD, SPEED AND SLOPE BY USE OF ACCELEROMETRY

2.1 Introduction

One of the parameters that affect the physical load of military is the weight of the backpack that is worn. In this study a tri-axial accelerometer (SPI-Elite, GPSports, Australia) is used to estimate whether load and velocity can be calculated by using impact peaks, step frequency and step size.

The SPI Elite is a small device worn in a specially designed mini back pack. It records position, time, body movements, impacts and heart rate continuously.

2.2 Methods

Eight healthy male subjects participated in this study (age 39±8.6 year; length 182±9.0 cm; weight 78±10.8 kg). The subjects performed a test protocol on a treadmill (Woodward – ELG70), carrying a backpack (untrained in carrying backpacks). Variations are made in velocity (3, 5 and 7 km/hr), load (0, 11.4, 23.9 and 36.4 kg) and slope (0 and 5 %).

2.2.1 Data Processing

Impact

The Accelerometer measures acceleration in three orthogonal directions, expressed in gravitational acceleration (g). These vectors are combined using vector analysis. Peaks in the combined signal are selected and divided in 6 zones in terms of size. The number of spikes in each zone is visible. These zones are manually set.

The SPI Elite software was not sufficient to determine the impact of each step. To assess the value of the impact of each step, a special software program was written, using MATLAB software. This program loads the SPI Elite data. Data blocks of the different load steps are split. To obtain reliable data the first and last 15 seconds of each block are cut out. The remaining blocks for analysis are therefore 2.5 min. Subsequently, this signal was filtered and the highest impact peak of each step was saved. By counting the number of peaks the number of steps is known. Because the distance covered was also known (5 km/hr during 2.5 min = 208 m), the average step size could be calculated.

Body Load

In addition to impact SPI Elite calculates “Body Load”, a standard for the load on the subject during the measurement. Body Load is the sum of all forces on the subject and can be calculated by multiplying the weight of the subject by the gravitational acceleration (g).

2.2.2 Statistical Analysis

Statistical analysis was performed using SPSS (version 15.0) One-way ANOVA is used to show differences between workloads steps, both of impact measurements as well as the step frequency and step size. When data analyses revealed a significant difference, a Tukey Honest Significant Difference (HSD) post hoc analysis was used for post hoc comparisons. Correlation is expected between velocity and impact measurements. Pearson’s correlation coefficient is calculated and, using linear regression, an equation is made.

2.3 Results

Table 4 presents impact, step frequency and step size for all different conditions (speed, slope and load backpack).

Table 4: Impact force (g), step frequency (n/min) and step size (cm) for 9 workload steps.

Workload step			Parameter: Impact (*g*)		step frequency (*n/min*)		step size (*cm*)	
	1	*3 km/hr*	1,34	±0,05	91.3	±5.0	54.9	±3.0
	2	*5 kmhr*	1,58	±0,13	109.3	±3.3	76.3	±2.3
	3	*7 km/hr*	1,94	±0,17	126.0	±4.2	92.7	±3.0
	4	*3 km/hr – 5%*	1,34	±0,04	88.9	±5.6	56.5	±3.6
	5	*5 km/hr – 5%*	1,59	±0,06	107.2	±3.1	77.8	±2.1
	6	*7 km/hr – 5%*	1,89	±0,15	127.4	±4.3	91.7	±3.1
	7	*5 km/hr – 11.4kg*	1,51	±0,07	110.6	±3.8	75.4	±2.6
	8	*5 km/hr – 23.9kg*	1,54	±0,06	111.6	±3.8	74.7	±2.6
	9	*5 km/hr – 36.4kg*	1,57	±0,08	113.0	±3.4	73.8	±2.2

Table 5 shows significance for impact force, step frequency and step size between workload steps.

Table 5: Significance between different workload steps.

workload step	1	2	3	4	5	6	7	8	9
1									
2	*^"								
3	*^"	*^"							
4		*^"	*^"						
5	*^"		*^"	*^"					
6	*^"	*^"		*^"	*^"				
7	*^"		*^"	*^"		*^"			
8	*^"		*^"	*^"		*^"			
9	*^"		*^"	*^"		*^"			

= sig. impact < 0.05;
^ = sig. step freqency < 0.05;
" = sig. step size < 0.05

2.3.1 Impact

The results of the mean impacts show (fig 2) that when velocity increases, the average impact also increases both with and without the influence of a slope. Additionally, this slope of 5 % did not affect the impact. When increasing the load of the backpack, the value of the average impact slightly increases. It is striking that in load carrying the impact on average is smaller than during walking without load (both with and without slope).

One-way ANOVA for impact measurements (table 5) shows an F-value of 33.442 ($P<0.05$) meaning there is a difference between workload steps. Tukey HSD post hoc analysis indicates a significant difference between the velocities, but not for influence of slope or weight.

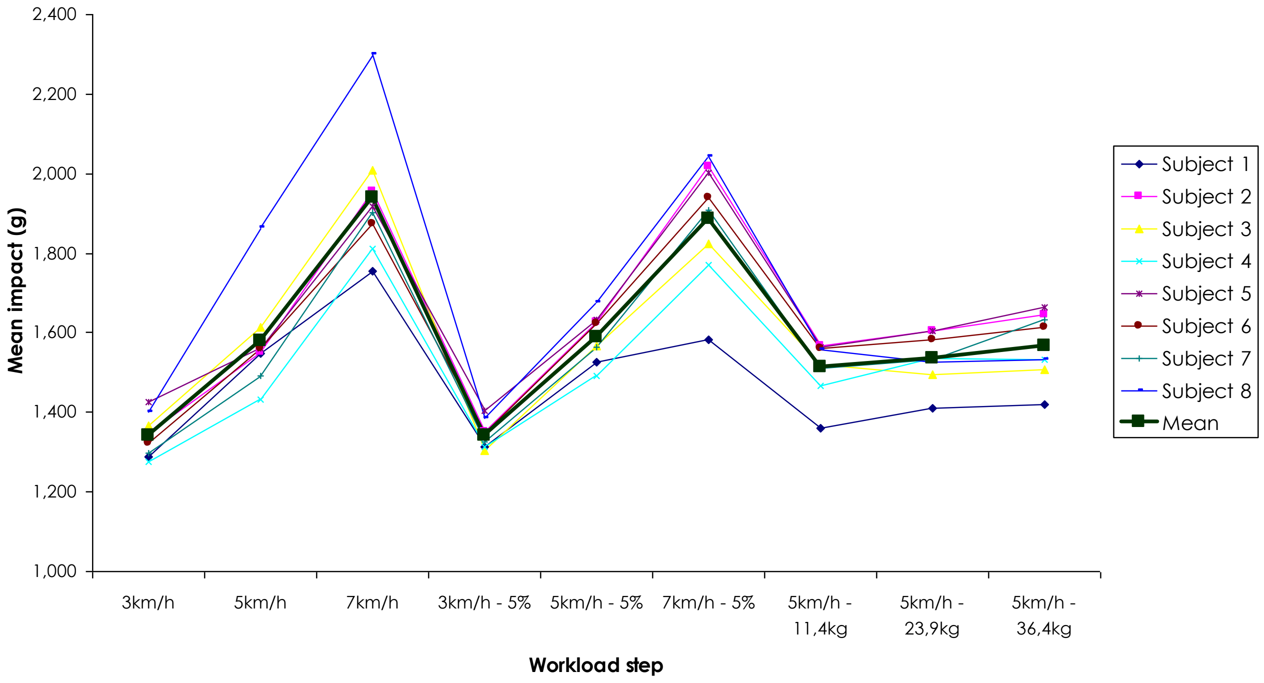

Figure 2: Mean impact (g) for all subjects and for the mean for 9 different workload steps.

2.3.2 Step Frequency

Step frequency (fig 3) shows the same pattern as impact. Step frequency sharply increases as velocity increases. An increase in backpack load results in slightly higher step frequency values.

One- way ANOVA for step frequency shows an F value of 79.962 ($P< 0.05$). Tukey HSD post hoc analyses indicate statistical differences between the velocities, but not for slope or backpack load.

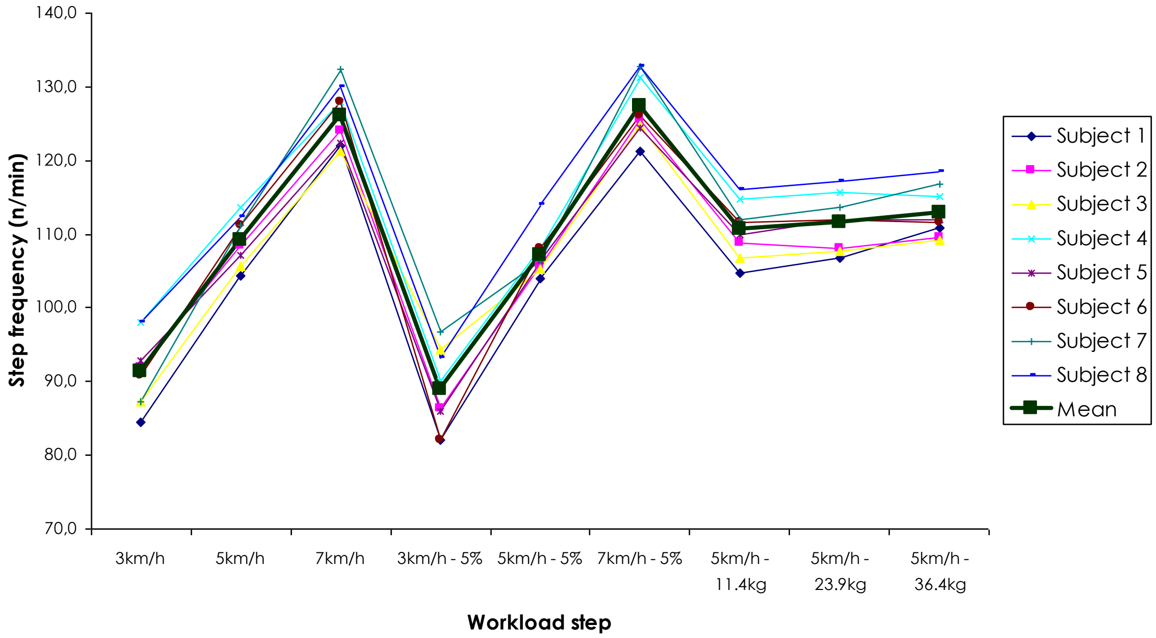

Figure 3: Mean step frequency (n/min) for all subjects for 9 different workload steps.

2.3.3 Step Size

Step size data are presented in figure 4. Step size increases by increasing velocity. Slope seems to have a small effect on step size. Step length slightly decreases when the backpack load increases.

One- way ANOVA for step size shows an F- value of 176.265 ($P<0.05$). Post Hoc analysis (Tukey HSD) indicates a significant difference between velocities, but not for the influence of slope or backpack load.

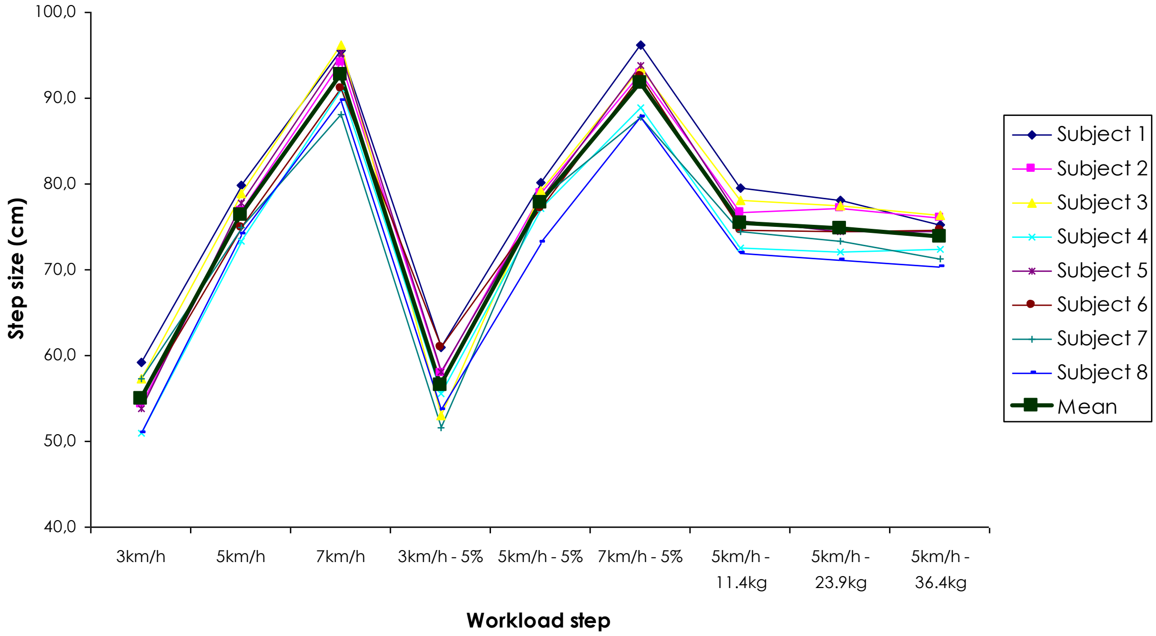

Figure 4: Mean step size (cm) for all subjects and for the mean for 9 different workload steps.

2.3.4 Regression Analysis (Velocity)

As expected (fig 2) impact correlates with velocity: Pearsons R = 0.878 ($p<0.05$). Regression analysis reveals an equation to calculate velocity when average impact is known:

$$\boldsymbol{v} = \mathbf{I * 5.395 - 3.569}$$

v = velocity (km/hr) and I is the average impact in g

This regression equation has an SEE of 0.648 and R^2-adj=0.767. This means that almost 77% of the velocity can be predicted on the basis of an impact measurement. This estimate has a probability of 95% to be correct (± 1.27 km/hr).

Other variables are added to the regression equation to make a better estimate. Step frequency appears to be a good addition. The new regression equation has an SEE of 0.397 and a R^2-adjusted of 0.913. This means that no less than 91.3 % of the velocity can be predicted from impact and step frequency:

$$\boldsymbol{v} = \mathbf{I * 1.812 + SF * 0.072 - 5.729}$$

v = velocity (km/hr), I = mean impact, SF = step frequency (steps/min).

For example, when the estimated velocity is 5 km/hr, with 95% certainty the actual velocity is between 4.22 and 5.78 km/hr.

2.4 Discussion

This study indicates that impact measurements are not predictive enough to calculate backpack weights. This is surprising because in previous studies (8) there was a significant difference between accelerations, measured on the backpack with different loads. Apparently it matters where the acceleration sensor is placed. When placed on the backpack, it follows the movements of the backpack. It is expected that this movement causes larger signal peaks with higher loads.

Impact measurements and step size can predict velocity. As previously demonstrated, GPS receivers are not reliable in urban and forest area (13). These results can help to increase accuracy. For example, with poor GPS connection (less than 4 satellites) velocity can be calculated using the accelerometer values. SPI Elite (GPSports) claims this too, but the results of the measurements show it does not.

Moreover it is debatable whether the GPS tool is necessary with an explained variance of 91 %. Further investigation is needed including more subjects and velocities.

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3.0 STUDY 3: QUALITY OF GPS SIGNAL IN MEASURING DISTANCES AND VELOCITY

3.1 Introduction

GPS data are known to be less accurate in measuring distance in urban areas or in forests. In this study, different GPS systems (SPI Elite, GPSports, Australia and FRWD, FRWD systems, Oulu Finland) were compared in forest and urban areas. GPS systems use the Doppler frequency shift method to calculate velocity. It is doubtful whether this instantaneous velocity is also true when it is averaged over a longer period.

In addition the SPI Elite uses an accelerometer to correct the distance measured using GPS positions. The distance measured by GPS and the corrected distance will therefore be compared.

3.2 Methods

Four subjects tested 8 SPI Elite systems and 4 FRWD systems simultaneously. They walked a track twice under two different conditions: urban area and forest. In urban areas the track was curved and non-curved. In the forest the subjects walked one track back and forth because there was no curved track. A measuring wheel was used to calibrate the track. The average number of active satellites was counted.

3.3 Results

Table 6 presents GPS data in urban area for a straight and curved track. Results are presented for SPI Elite and for FRWD.

Table 6: Distance, speed and active satellites in urban area for a straight and curved track.

		Urban area													
		straight							curved						
		Δx (m)	Δx* (m)	t (min)	V_{dop}	v	v*	Sats	Δx (m)	Δx* (m)	t (min)	V_{dop}	v	v*	Sats
subj	distance:	917,2		09:30		5,8			1001,4		09:48		6,1		
1	SPI 2	988,6	983,3	09:27	5,5	6,3	6,2	3,1	1379,4	1379,3	10:04	5,8	8,2	8,2	3,5
2	SPI 3	1074,6	1073,6	09:28	5,1	6,8	6,8	3,6	1080,6	1080,2	09:59	5,2	6,5	6,5	4,4
3	SPI 4	997,3	995,2	09:23	5,1	6,4	6,4	3,2	1080,9	1079,9	09:36	5,2	6,8	6,7	3,2
4	SPI 5	1052,2	1051	09:33	5,1	6,6	6,6	3,3	1125,0	1123,8	09:43	5,2	6,9	6,9	4,1
4	SPI 7a	980,9	979,5	09:36	5,1	6,1	6,1	3,4	1204,7	1203,9	09:43	5,2	7,4	7,4	3,7
3	SPI 8a**	696,8	695,3	07:11	5,4	5,8	5,8	3,2	1162,1	1159,6	09:54	5,5	7,0	7,0	3,2
2	SPI 9a**	756,4	755,8	07:11	5,3	6,3	6,3	3,5	948,8	948,8	08:24	5,4	6,8	6,8	3,5
1	SPI 10a	987,7	981,4	09:33	5,6	6,2	6,2	3,8	1127,8	1127,4	09:54	5,4	6,8	6,8	4,5
1	FRWD 1	1027,0		09:13	4,8	6,7			1046,0		10:01	5,1	6,3		
2	FRWD 2	897,0		09:27	4,8	5,7			1318,0		10:18	6,2	7,7		
3	FRWD 4	933,0		09:09	5,3	6,1			945,0		10:57	3,3	5,2		
4	FRWD 5	986,0		10:09	4,4	5,8			1024,0		09:00	3,9	6,8		
	Mean SPI	941,8	939,4		5,3	6,3	6,3	3,4	1138,7	1137,9		5,4	7,1	7,1	3,8
	SD SPI	*137,9*	*137,4*		*0,2*	*0,3*	*0,3*	*0,2*	*123,0*	*123,0*		*0,2*	*0,5*	*0,5*	*0,5*
	Mean FRWD	960,8			4,8	6,1			1083,3			4,6	6,5		
	SD FRWD	*57,3*			*0,4*	*0,4*			*162,4*			*1,3*	*1,0*		

x* = corrected distance using accelerometer and GPS data
Vdop = velocity based on GPS data (Doppler method)
v and v* = calculated velocity (x resp. x* divided by t)
Sats = number of active satellites
** = missing data

Table 7 shows GPS data in forest for a straight and curved track. Results are presented for SPI Elite and for FRWD.

Table 7: Distance, speed and active satellites in forest for a straight and curved track.

		Forest													
		forth							*back*						
		Δx (m)	Δx* (m)	t (min)	V_{dop}	v	v*	Sats	Δx (m)	Δx* (m)	t (min)	V_{dop}	v	v*	Sats
subj	distance:	1000,9		10:34		5,7			1000,3		10:28		5,7		
1	SPI 2	987,9	987,9	10:32	5,0	5,6	5,6	4,9	1007,4	1000	10:29	4,8	5,8	5,7	5,1
2	SPI 3	1005,6	1003,3	10:34	4,6	5,7	5,7	5,6	1052,6	1049,7	10:32	4,7	6,0	6,0	3,4
3	SPI 4	1029,8	1029,4	10:35	4,9	5,8	5,8	4,0	1087,9	1081,5	10:34	4,3	6,2	6,1	3,0
4	SPI 5	1012,5	1011,6	10:37	4,8	5,7	5,7	5,3	1015,6	1006,9	10:37	4,2	5,7	5,7	5,2
4	SPI 7a	1019,4	1018,2	10:40	4,9	5,7	5,7	5,3	1011,4	1006,3	10:29	4,7	5,8	5,8	5,3
3	SPI 8a**	768,0	767,7	07:38	4,9	6,0	6,0	4,1							
2	SPI 9a	1020,1	1020,1	10:36	5,1	5,8	5,8	4,1	1067,1	1057,6	10:35	4,8	6,0	6,0	4,4
1	SPI 10a	999,4	998,6	10:37	5,0	5,6	5,6	6,6	1000,0	991,8	10:31	4,8	5,7	5,7	6,5
1	FRWD 1	1042,0		11:02	4,6	5,7			979,0		11:03	4,5	5,3		
2	FRWD 2	1145,0		12:30	4,2	5,5			992,0		10:51	4	5,5		
3	FRWD 4	908,0		09:54	3,7	5,5			1003,0		10:42	3,5	5,6		
4	FRWD 5	1092,0		12:33	3,1	5,2			1063,0		12:53	3,1	5,0		
	Mean SPI	980,3	979,6		4,9	5,8	5,8	5,0	1034,6	1027,7		4,6	5,9	5,8	4,7
	SD SPI	*86,8*	*86,6*		*0,2*	*0,1*	*0,1*	*0,9*	*34,3*	*34,7*		*0,3*	*0,2*	*0,2*	*1,2*
	Mean FRWD	1046,8			3,9	5,5			1009,3			3,8	5,3		
	SD FRWD	*101,6*			*0,6*	*0,2*			*37,2*			*0,6*	*0,3*		

x* = corrected distance using accelerometer and GPS data
Vdop = velocity based on GPS data (Doppler method)
v and v* = calculated velocity (x resp. x* divided by t)
Sats = number of active satellites
** = missing data

3.3.1 Distances

The SPI Elite differs in urban area on the calibrated straight track on average 24.6 m (2.7%) and on the curved track on average 137.3 m (13.7%) and in forest respectively – 20.6 m (2.1%) and 34.3 m (3.4 %).

The FRWD differs in urban area on the calibrated straight route on average 43.6 m (4.8%) and on the curved route 81.9 m (8.2 %) and in forest respectively 45.9 m (4.6 %) and 9.0 m (0.9%).

3.3.2 Velocity

The velocity measured by the Doppler method (SPI Elite) underestimated velocity in urban area by 0.6 km/hr. In forest the underestimation is 1 km/hr.

The FRWD (Doppler method) overestimated in one case (FRWD 2: Forest) the actual velocity. In all other cases the FRWD underestimated the average velocity: 1.3 km/hr (urban) and 1.9 km/hr (forest).

3.3.3 Satellites

Figure 5 shows the number of linked satellites and the absolute difference in distance between the calibrated distance and distance measured by SPI Elite. It is clear that the greater the number linked satellites, the lesser the error in measured distance. Keep in mind: SPI Elite stops measuring when the connection is weak.

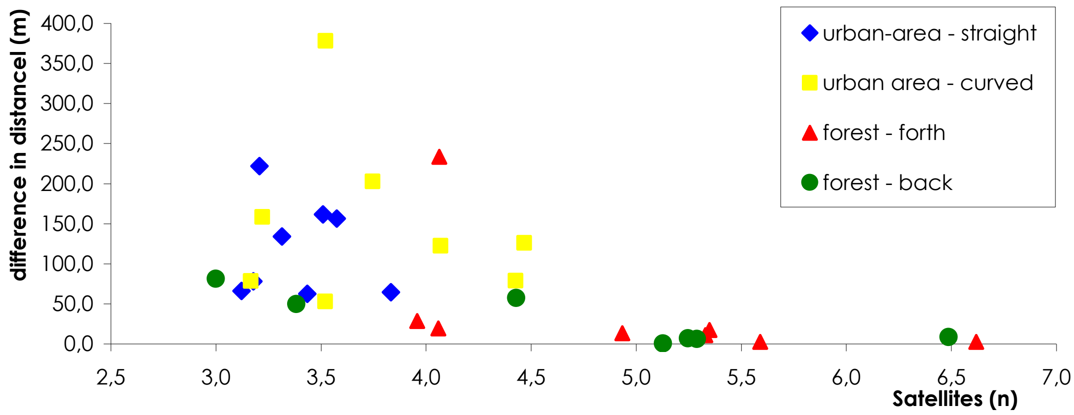

Figure 5: Number of satellites and difference in distance (m).

3.4 Discussion

The measured distances of the SPI Elite show a relatively large deviation in urban area (2.7 % and 13.7 %) and a lesser in forest (2.1% and 3.4%)

Regarding the SPI Elite velocities the following conclusions can be drawn:

- In both urban area and forest the SPI Elite underestimates velocity (Doppler method): mean difference: 0.6 km/hr and 1.0 km/hr.
- The calculated velocity (distance divided by time) is overestimated in urban area (mean difference 0.8 km/hr and 0.8*km/hr). In forest however velocity is fairly accurate (mean difference 0.2 km/hr and 0.1*km/hr).

Data of the FRWD show a larger spread than the SPI Elite (3 out of 4 measurements). However, SPI Elite measurement 1 shows a large spread because two systems (8a and 9a) did not measure the whole distance. Furthermore, the FRWD velocity (Doppler method) underestimates velocity even more than the SPI Elite does.

This shows that velocity according to the Doppler method is not suitable to estimate average velocity over a certain period (SPI elite and FWRD). The Doppler method is more suitable for measuring instantaneous velocities because it is less sensitive to outliers of distance determination using GPS.

Furthermore, it appears there is a relationship between the accuracy of the measured distance and the number of satellites which are linked. When connected to an average of 4.5 satellites, the difference in distance is less than 50 m /1000 m (5%).

The effect of accelerometer correction on the measured distance is minimal and has no effect on the average velocity. It also shows that this correction reduces the measured distance, in contrast to the manual. It says that it only adds extra distance.